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BOUNDARY LAYER CONTROL BY MEANS OF SUCTION

G. Maillart

(NASA-TM-75502) BOUNDARY LAYER CONTROL BY MEANS OF SUCTION (National Aeronautics and Space Administration) 45 p HC A03/MF A01 N80-17987
CSCL 01A Unclas
G3/02 33197

Translation of "Aspiration de la couche limite", Ministere de l'Air. Publications Scientifiques et Techniques. Bulletin des Services Techniques 106, April 1947, 35 pages.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D.C. 20546 JANUARY 1980

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BOUNDARY LAYER CONTROL BY MEANS OF SUCTION

G. Maillart
Societe Rateau

Introduction

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The present study was undertaken at the request of the Toulouse Institute of Aeronautical Experimentation and Research by the Societe Rateau, which had undertaken an experiment to rectify a model of an aerodynamic wind tunnel, for which the length of the diffuser had to be reduced, using the potentialities of boundary layer control by means of suction.

The engineer charged with this question, Maillart, was led, in order to answer the request of the Toulouse Institute of Aeronautical Experimentation and Research, to undertake the problem and to write at that time (i.e., in 1943) a report which constitutes the study published today.

The experiments undertaken were later finished and allowed attainment of highly encouraging results which will be published eventually. They particularly showed that wind tunnels could be constructed with very short diffusers and with coefficients of use equal to those realized in normal wind tunnels, and this taking into account the power necessary for suction.

Since that time, the Societe Rateau has continued the examination and use of possibilities offered by boundary layer control by means of suction. In particular, since the liberation of that territory, it has pursued the study of its principal applications; that is, those related to aviation, a study it began in 1939, from the time when it became interested in jet propulsion.

The work which constitutes the subject of this publication thus

* Numbers in the margin indicate pagination in the foreign text.

is very incomplete from this viewpoint and further developments, which will eventually be the subject of later communications, will be necessary.

I. Generalities. The Various Methods of Boundary Layer Controls /3

The occurrence of friction between fluids and fixed walls is the cause of all the differences that can be noted between actual and theoretical flows. Contrary to the conception of the mechanics of theoretical fluids, fluids adhere to the walls and the transition of the speed of the de-energized current to the wall occurs progressively. When the speeds are high enough, this transition occurs within a relatively thin layer, called the boundary layer.

The tangential forces of friction that are produced at the wall are part of the resistance of obstacles: this is friction resistance. It is not the only one, however, and there is another, constituted by the perturbations which the effects of friction cause within the distribution of normal effects: this is shape resistance.

As long as the boundary layers remain very thin, the flow of fluid outside them is not very close to the theoretical flow and the distribution of pressures is only slightly modified: the shape resistance is weak. However, it is not always so and, as we know, in all the regions where the streams of the boundary layer are subjected to too great a slowing, separations of streams can arise and, from the, results a considerable increase in the shape resistance and a decrease in lift.

The intensity of these various effects is linked to the constitution of the boundary layer and the reduction of these effects by action upon the latter is a natural idea which is as old as the theory of the boundary layer.

The most serious effect, i.e., that which is most likely to separate actual flows from the theoretical flows, is constituted by the separations. It was in order to avoid these that boundary layer control was first attempted. They are produced when the curve of speeds is sufficiently attenuated by the effect of the general slowing. Since the boundary layer is composed of streams whose energy is reduced, it is necessary either to give them a new complement of energy or to replace them with others that do not have this deficiency; hence, the different ideas that have arisen concerning the various methods of action to use.

It is natural to try to eliminate the exhausted streams by evacuation through the walls; they are then automatically replaced by adjacent sound streams which come in contact with the wall and so, stemming from the evacuation slot, a new boundary layer is formed, more likely than the old one to resist subsequent separations. This /4
is boundary layer control by means of suction.

One can also try to repel the exhausted streams away from contact with the wall, by interposing higher energy fluid streams between the boundary layer and the wall. These can be induced by an outside medium: this is boundary layer control by means of streaming; the new layer, once injected, is in this case submitted not only to friction on the wall, as in the preceding case of suction, but it must also have sufficient energy to be able to draw along the streams of the old layer, which were slowed by the previous friction. In the case of streaming, one is in control not only of giving this new layer a certain thickness but also of giving it a certain desired speed.

Streams taken within the fluid itself, in a high-energy portion (i.e., outside the boundary layers) can be interposed between the boundary layer and the wall. This procedure, which has the advantage of requiring neither supplementary energy nor any special apparatus, does however require certain precautions: it is obviously necessary that the friction within the inflow channels of these streams not be such that the injected layer is as exhausted as the one it is to replace; it is therefore necessary to take the replacement streams in the neighborhood of the point of impact or in the high pressure areas where the speed is slight enough and conduct them to the injection points selected by convergent channels, as short and as slightly curved as possible.

There is no reason to believe that suction should a priori give better results than boundary layer control by means of streaming. In addition, the experiments conducted up to the present time, as faras these various procedures are concerned, are not numerous enough to allow definite conclusions.[1]

Since 1904, when the first experiments on boundary layer control by means of suction were done by Prandtl, many experiments have been performed involving suction as well as streaming, and many publications concerning these different procedures have appeared. The bibliography relevant to slotted airfoils is especially large, which could explain the great development the latter have undergone.

The present study, however, will be more specifically devoted to study of boundary layer control by means of suction and, in the following text, we shall try to expose how this important question appears today, with consideration given to the various experiments that have been published up to the present.

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[1] In the process of streaming with streams taken within the fluid, however, the necessary precautions are such that in practice, this process is used only in the case of slotted airfoils, where its advantages of simplicity have allowed considerable development of the latter. In many cases, the regions where it is possible to select the necessary streams are very restricted and it is impossible to lay out channels of suitable form up to the position of the slot, which often is rather far from those regions. Certain unpublished experiments, performed at the N.P.L., would justify this logical opinion, which is expressed in the work Modern Development in Fluids Dynamics, edited under Goldstein's direction and in which an entire chapter is devoted to methods of boundary layer control.

According to the amount of evacuated fluid, a more or less large portion of it can be removed, reaching the entirety of the practical thickness of the boundary layer. /6

Let us specifically study this effect. Let us suppose to be known the evolution of a boundary layer along a wall of an ordinary shape (which we shall assume to be a plate for the sake of simplicity, and also because this assumption is logical, in virtue of the local character of the phenomenon); this boundary layer is, of course, assumed to corr spond to ordinary pressure conditions; i.e., to an evolution of the speeds of the sound flow, which is given a priori and corresponds, for example, to a slowing; we shall assume only that the portion of the layer on which the suction is performed is located upstream of all possible separation.

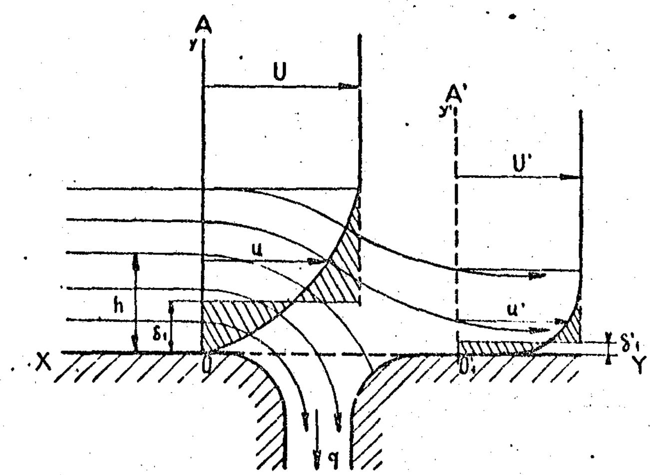

Figure 1

This layer can be laminar or turbulent. We shall not predict further how its constitution is known, whether by experiment or by calculation; in the case of a laminar layer, the calculation can be done when the pressure distribution is given; in the case of turbulent conditions, in every state of cause, and in the present state of our understanding, only semi-empirical calculations can be made, based on the corresponding theories of turbulent boundary layers.[2]

If the layer does not separate and remains thin everywhere, the distribution of pressures on the wall is obviously the theoretical distribution. More exactly, it is that which would be produced in the theoretical flow of a fluid around the same obstacle, assumed to be <u>thickened</u> at each point of the value at which the slowing of the boundary layer draws the sound streams away from the wall. It is, as in the literal translation of the German expression "Verdrangungsdicke" and the English "momentum thickness," the thickness of displacement can be determined from the speeds within the boundary layers:

$$\delta = \frac{1}{U}\int_0^\infty (U - u)\, dy \qquad (1)$$

We can define the lines of current of the boundary layer from the continuity equation and also know the value of the amount of fluid contained at each point of the wall, up to a given distance of the latter. Suppose we wanted to apply suction to a certain amount q of fluid. We can do it in an infinite number of ways. The simplest is to make a slot in the wall and suction out the desired amount of fluid; in so doing, the lines of the current in the boundary layer are disturbed, since one of them is at a distance h from the wall it must, after the slot, come in contact with the wall (Figure 1).

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[2] See, for example, an excellent summary of the corresponding methods in <u>Modern Developments in Fluid Dynamics</u>, Goldstein, chap. IV, volume I, "The mathematical theory of motion in a boundary layer."

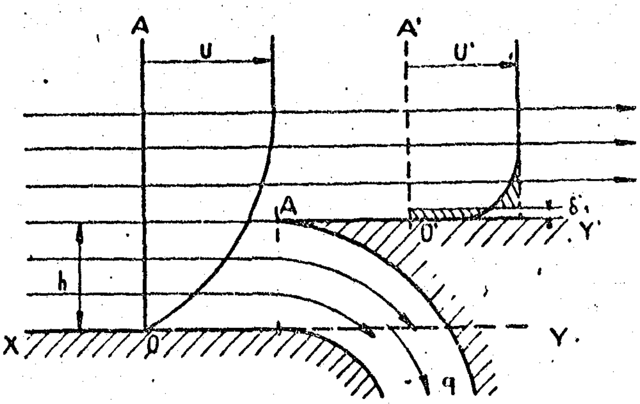

Figure 2

The combination of the boundary layer and the neighboring sound fluid must follow this movement, which modifies the pressure conditions. This is the well effect, described by Prandtl[3] and Schrenk[4]. We shall return to it.

We may also assume that the wall is displaced by the amount <u>h</u> (Figure 2), with the suction taking place in the space thus created. In so doing, the flow of sound fluid is not changed by the suction; in other words, the value of the total displacement thickness in relation to the old wall XY is not greatly modified.

b) <u>Effect of a Slot on the Distribution of Pressures</u> /1

In the general case where the wall is not displaced, a sharp break in the fictitious wall causes a change in the pressure conditions. By going in the direction of the flow, there result pressure drops

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[3] See, for example, <u>Buri Dissertation</u>, Zurich, 1931. See also Prandtl, <u>Aerodynamic Theory</u>, 1935, 3, pp. 155-160 and Goldstein, <u>Modern Developments in Fluid Dynamics</u>, vol. II, pp. 436-438.

[4] If there is no separation, the flow can be calculated by the theory of perfect fluids, by adding to the wall upstream of the slots by increased thickness equal to the displacement thickness δ_1 and equal to δ_1. Besides, the decrease in flow q is equivalent to a breakage in the hypothetical wall equalto q/U. so that in the case of Figure 1, the displacement of the hypothetical wall is $(\delta_1 - \delta'_1 + \frac{1}{U})$, which can easily be verified to be equal to h. In the case of Figure 2, this breakage is cancelled by the shifting, which has exactly the value of h.

upstream of the slot and pressure rises downstream, which are superposed on the evolution of the combined pressures.

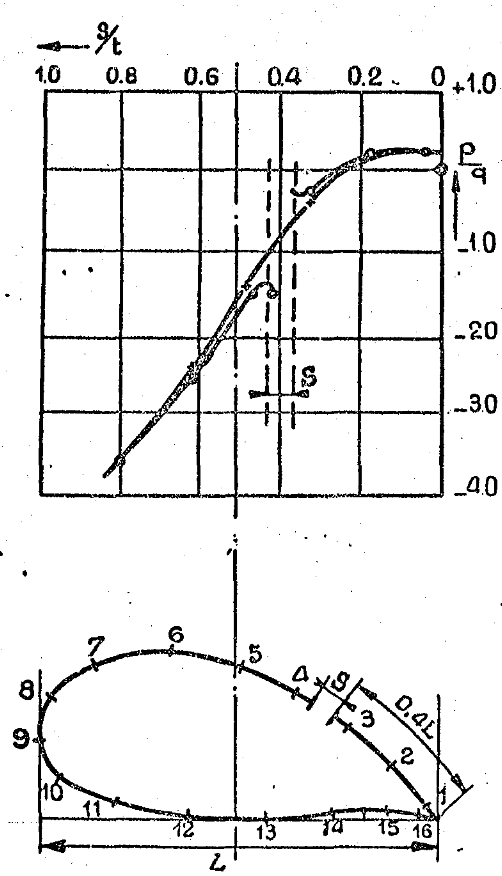


Figure 3

This effect, which was observed by Schrenk in suction experiments on an airfoil, is perceptible at a rather large distance from the slot. Figure 3, which reproduces the experimental results of said author shows that it is perceptible over more than 2/10 of the depth of the wing at each side of the slot.

This effect was studied in greater depth by Cerber [4] among the experiment which that author performed, certair ones concerned the effect of a slot in the flat wall of a channel, facing an adjustable wall, adjusted so that the pressure upstream and downstream of the slot were the same; this wall thus must compensate for the breaking of the fictitious wall, caused by the slot, in such a way that the measured drops and rises are entirely attributable to the well effect. The contrivance of the experimental channel

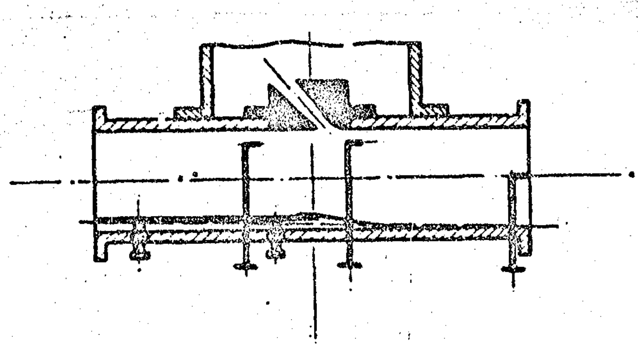


Figure 4

is schematically represented in Figure 4, with the results of the measurements in Figure 5, taken from the original publica- publication.

In the influence of the slot on the pressure conditions, it is necessary to distinguish two effects:

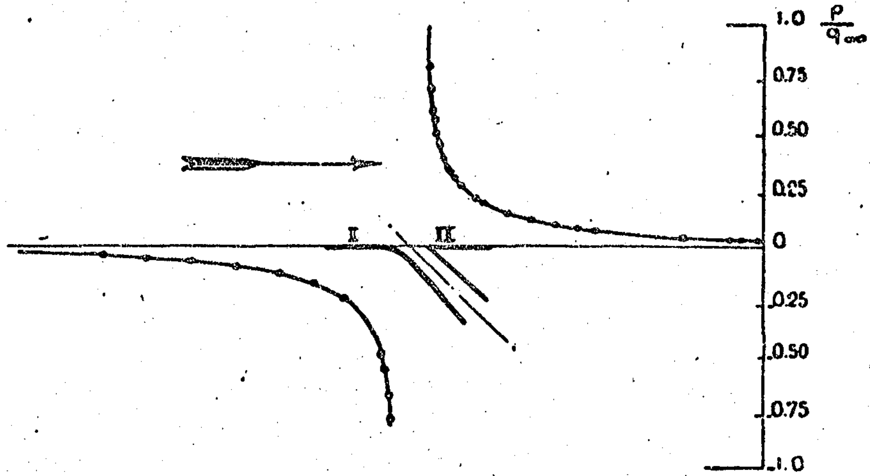


Figure 5

1. One effect, which could be characterized as primary and which is due to the general breaking of the entire section of the fictitious wall located after the slot. This effect is eliminated or at least considerably attenuated if, for example, this displacement /1

is compensated incidentally, as was the case in Gerber's experiments.

2. The well effect, which is produced locally in the neighborhood of the slot, is above all due to the fictitious breakage produced by the slot being created abruptly. It causes pressure drops upstream and pressure rises downstream. This effect certainly depends on the shape of the slot and especially on its width. It naturally depends also on the amount of evacuated fluid.

These two effects are obviously very difficult to separate. In Gerber's experiments, for example, it is certain that the experimental results represented in Figure 5 depend to quite a significant degree on the manner in which the breakage of the main wall which compensates the diminution in the amount of fluid is regulated. This wall consisted of two right sections joined in a progressive fashion, with the region of juncture located in front of the fissure and having an a priori fixed length and a shape not easily modified at will. It is certain that the results would have been different if any other shape had been used and in particular, if a rectilinear wall had been used, as shown by the dotted line in Figure 4.

The primary effect on the distribution of pressures is particularly noticeable when a channel (for example, that of a diffuser) is involved, and it is obviously all the more marked as the suctioned flow is large in relation to the total flow. Some unpublished experiments, done in 1942 at the Societe Rateau on a diffuser with boundary layer /11
control by means of suction show (Figure 6) that the corresponding recompression that occurs is a not insignificant part of the total recompression to be effected.

Note. - The primary modification of pressures and the well effect caused by a slot, since they have an action that extends more or less upstream, obviously act upon the constitution of the boundary layer at that site. The pressure drops due to the well effect, which correspond to a local acceleration, have in particular the very clear

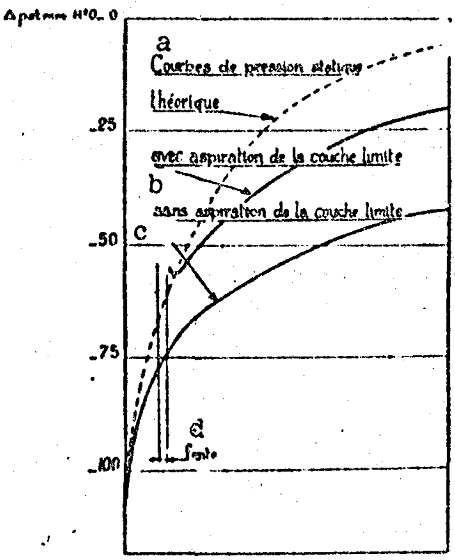


Fig. 6. a) Theoretical static pressure curves; b) with boundary layer suction; c) without boundary layer suction; d) slot.

effect of restricting its development.

c) <u>Influence of the Shape of the Slot. Characteristic Curves of a Given Slot</u>

The curve of distribution of pressures on the wall and, in general, all the characteristics of the flow in the immediate neighborhood of the slot, depend greatly on the shape of the latter. The slot must be adjusted for the evacuation of the amount of fluid for which it is provided. Obviously, a determined amount of fluid can be suctioned with any slot; in order to attain this end, it suffices to use a large enough pressure drop in relation to the pressure that reigns within the principal flow at that site. There is, however, an obvious interest in reducing the necessary pressure drop as much as possible.

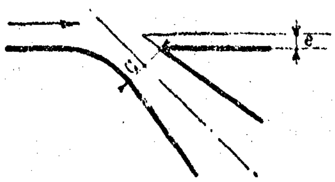
Furthermore, the shape of the slot must be adjusted to a proper evolution of the sheet of fluid assailing the new wall. Returning to Figure 1, it is seen that there is necessarily a stopping point on the back ridge of the slot. At that point, there obviously exists a pressure rise corresponding to the halting of the speed of the stream abutting at that point. If the boundary layer is evacuated entirely, this speed is that of the principal current, or else it is more or less inferior to it; beyond that point, on the new wall, the pressure decreases and gradually regains its normal value. Corresponding to this is a gradual expansion of the boundary layer, which is especially suitable to limit its thickening. If the shapes are ill chosen and, in particular, if the slot is too wide, this stopping point may be located on the inside of the suction channel and the convolution of the slot's back ridge may, if it is too sharp, be hazardous to a good conductance of the new boundary layer's streams.

There is also a certain interest in avoiding giving a large deviation to the suctioned fluid, for this would cause a pressure drop followed by a useless recompression within the convolution of the slot's front ridge. It is therefore necessary to slant the ridge as much as possible in the direction of the current, within the limit of possibilities for execution and to give the front ridge an amply sufficient roundness. In the same spirit, there is also interest in giving it the shape of a diffuser in order to maximally regenerate the kinetic energy of the suctioned portion which, without that, would be lost in the suction chamber. The width of the slot, of course, must be adjusted to the amount of evacuated fluid, in an attempt to obtain as continuous as possible a speed gradient for the suctioned streams.

The first experimenters used ordinary slot shapes, often consisting of a sharp interruption of the wall and sometimes made of a single sheet of metal. /12

Gerber, on the other hand, uses a logical form of slot (represented in Figure 7) which has, however, an angular back ridge.

The influence of slot shape was the subject of very few studies until Gerber's experiments. Many writers on this subject give opinions that are only valuable relative to the particular cases that constitute their experiments, and which in any case can only be taken as evidence, so long as many systematic experiments have not been performed. Besides, the first authors, lacking precise data, made



e/δ_0	c/δ_0				
0	4.86	3.7	3.0	2.25	1.55
0.3883	4.86	3.7	3.0	2.25	1.55
1.98	4.86	3.7	3.0	2.25	1.55

Figure 7

slots whose width, for example, was chosen a priori, and which was more or less naturally adjusted to the problem at hand.

Gerber performed some systematic experiments which are interesting to describe and to analyze in detail. In order to characterize a given slot and expedite the comparisons, however, it is first necessary to relate its effect to some dimensionless coefficients.

The flow suction per unit of length of the slot must be correlated to a reference length and speed. For the latter, it is logical to take the speed V_∞, or the theoretical speed of the sound current at a right angle to the slot, outside the boundary layer. As for the length, it is logical to take it relative to the dimensions of the boundary layer, immediately upstream of the slot.

Its thickness can be taken but it is always very ill defined and it is more worthwhile to take, for example, the displacement thickness. The momentum thickness λ, defined by the following equation, is also /13

$$\lambda = \int_0^\infty \frac{(U - u) \cdot u dy}{U^2}$$

As we know, in a continuous boundary layer, the gradients of λ

are related to the coefficeint of local friction[5], according to the momentum theorem.

We shall choose the displacement thickness δ as our reference length. A flow coefficient c_q can then be defined by the equation:

$$c_q = \frac{q}{\delta V_0}. \tag{2}$$

In truth, in each particular case any other characteristic can be used instead of the displacement thickness. For airfoils, for example, Schrenk and other authors use the depth of the wing. Gerber uses channel height but it is, at any rate, easy to make the necessary transpositions in each case.

In correlating q to a length related to the thickness of the boundary layer, it is necessary to observe that the reference varies with the Reynolds number used, which is inconvenient ; but it is, on the other hand, likely that the amount of fluid to be evacuated in each case is a set proportion (or the entirety) of the boundary layer, so that the value of the coefficient c_q corresponding to a given effect in each particular case has chances of being almost independent of the Reynolds number, which is an advantage.

Likewise, V_o can be replaced in each particular case by any other speed and, in the case of airfoils in particular, by the speed V_∞; this confers advantages when the positions of the slot and consequently V_∞, vary. The definition given above by equation (2), on the other hand, has the advantage of not being specific to the particular application of suction and because of this, is more general.

In order to evaluate the power expended to affect the suction, it is necessary to allow the suctioned fluid to be recovered in the suction chamber, recompressed by an adequate system and sent back into

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[5]Gerber also uses a thickness of pulse train length, defined by the equation:

$$\int_0^\infty \frac{(U^2 - u^2)\,dy}{U^2},$$

which has the advantage of being easily calculated by planimetry of the indications of a Pitot tube.

the sound fluid with the same energy that the latter's streams possess. The output of the fictitious compressor used may be assumed to be equal to 1, or to such a value as is deemed appropriate.

The second case corresponds more to reality but requires _a priori_ assumption of a figure that can be highly variable according to the case.

If P_o is designated as the static pressure in the sound fluid directly above or below the fissure, the corresponding speed being V_o and the static pressure in the suction chamber being P_{st}, the difference $\Delta p = p_o = p_{st}$ can be correlated with the level of speed, which defines a pressure coefficient c_p: /14

$$c_p = \frac{\Delta P}{\frac{1}{2}\rho V_0^2}. \quad (3)$$

The expenditure of energy, by unit of weight of suctioned fluid necessary to affect its return into the sound fluid, is obviously equal to:

$$(1 + c_p)\frac{1}{2}\rho V_0^2,$$

eventually multiplied by the inverse of the assumed output of the blower.

The coefficient c_p, like the coefficient c_q, is defined by equation (2), a very general coefficient that does not presuppose a particular application for which the suction is used.

Just as for this last, then, it may be more practical in each particular case to use a coefficeint related to other references; and for airfoils to p_∞ and V_∞, for example. In any event, the transpositions are easy to perform, as for c_q.

The effect of a suction must be measured by reduction in boundary layer thickness. The displacement thickness, momentum thickness, or any other dimension related to the boundary layer thickness can be taken. We shall choose the relation k of the displacement thicknesses upstream and downstream:

$$k = \frac{\delta}{\delta_0}. \quad (4)$$

For a given slot, two of the variables k, c_q and c_p are functions of the third.

The experiments done by Gerber involved slots defined by the sketch in Figure 7 and the corresponding Table. Since these experiments were the only ones concerning measurement of the effect of a certain number of slots and, because of their interest, we give below the results obtained by that author.

The slots used are marked by the correlation of the width of the slot's neck to the displacement thickness upstream. Furthermore, the author studied the influence of a shift θ of the walls, also marked by its correlatión to δ_o. To give an example, the action on the profile of speeds is given by Figure 8 for a particular case, with analogous action in other cases.

The experimental results given in the form of values of k and c_p /16
as functions of c_q, have been deduced from Gerber's results (Gerber uses slightly different references) and are the subjects of Figures 9 and 10.

In Figure 9 it is seen that in order to realize the same effect marked by a certain value of k, it is necessary to suction the same flow for all the slots.

Figure 10, on the other hand, shows very small and even negative values of c_p (the negative ones due to the diffuser's effect), to the advantage of wide slots, without finding an optimum value.

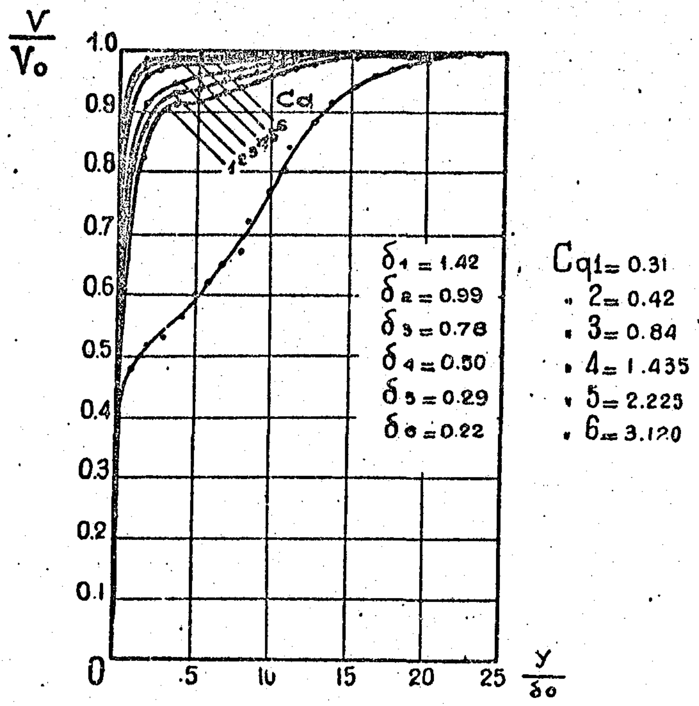

Figure 8

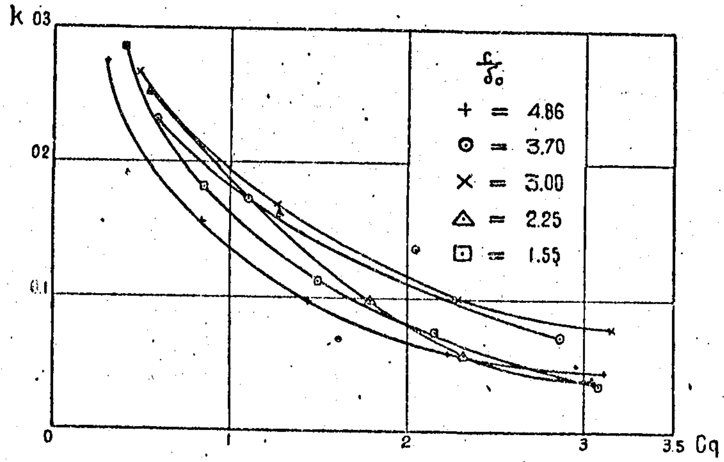

Figure 9

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This last fact can be explained by observing that when a wide slot is used, the stopping point at the back ridge has a tendency to be displaced toward the inside of the slot. There thus tends to be a benefit; for the fluid deducted beforehand, from the natural slowing that takes place in the neighborhood of a stopping point, which explains the greater value of the coefficient c_p obtained.

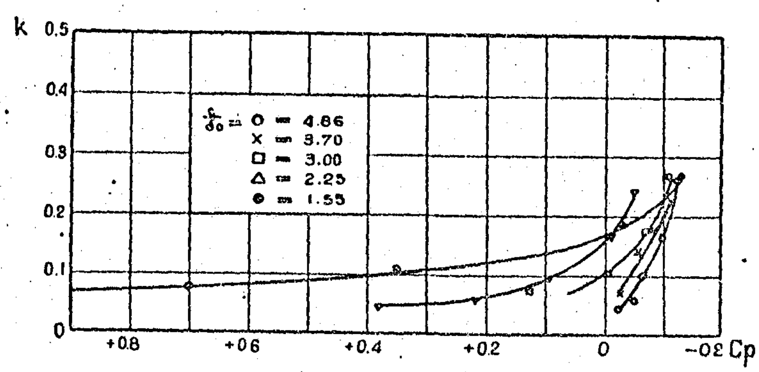


Figure 10

On the contrary, the principal flux must, beginning at a certain moment, pass around the back ridge of the slot, at the very least if its radius of curvature is insufficient, which can only be unfavorable to its evolution from the viewpoint of the friction coefficients. Thus there is probably an optimum, which can be determined only by comparing on the one hand the benefit achieved and, on the other hand, the extra friction that results from it. The latter, however, was not measured by Gerber, and it would be desirable to have those experiments completed in this sense. That would allow determination of whether an optimal width really exists, as is likely.

As far as the shape of the slots is concerned, it is also necessary to call attention to a particular experiment by Gerber (reproduced in Figure 11), which compares two slots that are identical except in the bending radius of the front ridge, which differs in the two cases.

Probes of the boundary ary layer done in total pressure have been performed in the two cases for an identical pressure drop in the suction chamber. They show an advantage for the greater rounding. The values of c_q have not been indicated but, as we know, they are almost independent of the shape of the slot and depend only on k. It is certain, according to the shape of the sounding curves obviously corresponding to different values of k, that for a single value of of c_p, the slot with greater rounding allows a greater flow. /1

A

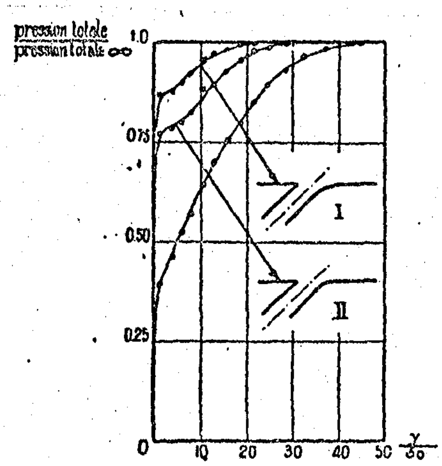


Fig. 11. a) Total pressure

It is the equivalent of a wider shape; that is, it corresponds to a greater resistance for the suctioned portion, which is logical; that is in accord with an assertion by Schrenk (10) that a rounding of the entrance ridge gives the same result as a widening of the slot.

Note. Gerber's experiments, which are the most complete ones we possess to date, correspond to a boundary layer of a fixed shape, obtained by a special procedure.

Strictly speaking, it is certain that the results must depend on the distribution of speeds in the boundary layer under consideraation, but it would be interesting to know whether the results obtained are highly variable or are almost independent of it; however, no completed series of experiments allows this question to be answered at present.

III. Applications. History

The first experiments of Prandtl in 1904 (6) had as their only goal to confirm the hypothesis which stated that separations arose from an instability in the boundary layer; they were performed on a circular cylinder and resulted in the proof that it was possible, by suctioning the boundary layer, to eliminate the vortex zone from the rear of uncontoured bodies and to reestablish the potential flow.

Boundary layer theory was still in its infancy, and no one at that time dreamed yet of the technical evolution of that process. It was only in 1923 that Ackeret and Betz obtained a patent in Germany for the application of boundary layer control by means of suction to lifting surfaces.

The first experiments on wings were published in 1925, in the provisional proceedings of the Gottingen Institute for Aerodynamic Experimentation (7). It concerned measurements done on a Joukowsky profile, in the course of which separation of the large angles of incidence was avoided by boundary layer control by means of suction.

In 1926, Ackeret published in V.D.I. (8) a study that can be considered the first general exposition of the subject. There for the first time other applications are discussed; in particular, diffusers, diminution of resistance of spheres and the deviation of a 180° stream with a unilateral alignment.

The same year, at Zurich, he presented his work and ideas at a lecture given on the occasion of the second International Congress of Applied Mechanics (9).

At about the same time, Schrenk published in Z.F.M. (10) the experiments done at Gottingen on spheres with boundary layer control by means of suction.

From that time on, the works specifically devoted to carrying wings with boundary layer control by means of suction multiplied, not only in Germany but also in other countries and especially in the U.S.A.

Schrenk's works were published in 1928 in Luftfahrtforschung (11), then in 1931 by Z.F.M. (12) and again in Luftfahrtforschung in 1935 (13).

In 1927, Perring and Douglas published their experimental results in A.R.C. Report and Memoranda (14), and then Bamber published his in 1931 in the N.A.C.A. Report (15) and in the two preliminary publications of the N.A.C.A. Technical Notes (16), (17).

As far as diffusers are concerned, the most interesting experi- /19
ments at the outset were Ackert's, published in V.D.I. in 1926, and then in France those of Margoulis, which were performed from 1930 to 1933 and published in 1934 in La Technique Aeronautique (18).

In the following sections, we shall examine the case of airfoils and then that of diffusers, which is of particular interest to us.

IV. Application to Airfoils

Boundary layer control by means of suction, judiciously applied, allows avoidance (at least within a certain limit) of the separations that occur at steep angle of attack and increase the lift of airfoils. However, it significantly changes the tangential forces and it is necessary also, as has been seen, to take account of the work expended, not only for the suctioning of the fluid but also for its return into the sound fluid.

In order to obtain the resultant of forces on an airfoil, it suffices, as we know, to apply the momentum theorem to the fluid contained in a closed contour surrounding the airfoil.

When it is an ordinary airfoil, by reducing that closed contour to the contour of the airfoil itself, the resultant is again found to be the sum of the normal and tangential forces on the wall. In the case of an airfoil with suction, it is moreover necessary to take into account the momentum corresponding to the suction and to the removal of the flow of fluid traversing the slot.

It is known how the normal forces vary on the profile. If the suction is effective and if no separation occurs, they can be calculated up to the neighborhood of the slot (with the secondary well effect put aside) by the theory of potential movement, by taking into account (for greater precision) displacement thicknesses at different points.

Let us note in this regard that, if the flow is two-dimensional, the removal of the surrounding suctioned fluid can only be performed at one point of the wall. It is evident that there is interest in removing it in the direction of the movement and at the back ridge. It is then necessary, strictly speaking, to take into account in the calculation the supplementary displacement thickness caused by this removal (corresponding source effect).

In the case that would involve an airfoil of limited span and where the removal would be done at a certain number of fixed points (whether distributed or not over the entire span), this would also be equivalent at that site to a certain increased displacement thickness.

a) Determination of the Resistance Due to Suction in the Case of a Flat Plate /20

In order to study the influence of suction on the tangential forces, with momentum taken into account, let us begin by assuming (for the sake of simplicity) that a flat plate is involved, with suction performed by displacement of the wall, in order not to have variation in the normal forces. Let us next apply the momentum

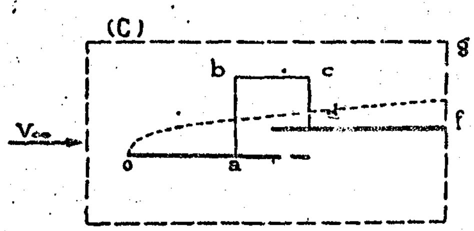


Figure 12

theorem to a contour abcd (Figure 12), consisting of two perpendiculars to the wall, located on both sides of the slot and a parallel bc, at a sufficient distance from the wall to be on the outside of the boundary layer.

Since there is no variation in the displacement thickness from a to d, there is no flux along bc and the suction of the boundary layer is equivalent to a force directed toward the rear; that is, unyielding and equal to the momentum F carried away by the suctioned fluid. The hypothetical removal, performed at the back ridge and at the speed of the sound fluid, is equivalent to a force directed toward the front, thus propulsive and equal to $\frac{IU}{g}$.

With E designating the energy expended for the extraction and removal, the equivalent resistance to the suction is equal to:

$$F+\frac{E}{U}-\frac{IU}{g}.$$

If the output of the pumping system is equal to unity, the expended energy E would be equal to:

$$\frac{IU^2}{2g}-e,$$

with e designating the energy possessed by the suctioned fluid at the site of its extraction.

Of course, to this amount the tangential forces on the plate, along oa and df, are added as resistance, it being understood that the length bc is negligible. These latter are equal to the momentum lacking in ab in relation to that in o; and to that in gf in relation to that in cd. In sum, taking account of the difference of momentums lacking in ab and cd, it is easy to see that the total resistance is:

$$\int_{fg} \frac{di}{g}(U - u) + \frac{E}{U},$$

which could also have been obtained directly by applying the momentum theorem to an ordinary contour C (Figure 12), completely surrounding the plate.

If the pumping system has an output equal to unity, the second term of the resistance can be written in the following manner, with u_o designating the speed of a stream at the moment of its suction, and u designating the speed of removal, which we shall assume to be different from U:

$$\frac{1}{U}\int_{\text{flux aspiré}} \frac{di\,(u - u_0)(u + u_0)}{2g}.$$

It is easy to see that the minimum total resistance is produced when the entire boundary layer is suctioned to the trailing edge and expelled to the atmosphere at speed U. The first term then cancels and the second is equal to:

$$\frac{1}{U}\int_{fg} \frac{di}{2g}(U^2 - v^2), \tag{5}$$

an amount less than the resistance without suction, which is equal to:

$$\int_{fg} \frac{di}{g}(U - u). \tag{6}$$

Suction thus theoretically causes a gain in resistance; however, it is necessary to observe that suction, since it is performed at the trailing edge, changes nothing in the tangential forces to which the body is submitted.

The entire difference, i.e., the increase, comes from the reaction produced by the ejection system, which thus seems like a momo-propulsive system. It is necessary to see what this increase corresponds to, which is easy.

Let us note that within an ordinary boundary layer, the resistance corresponds to an energy equal to RU (R designating the total resistance), which is necessarily expended in turbulence; one portion is within the boundary layer itself:

$$\int_{lg} \frac{di}{2g} (U^2 - u^2),$$

the other portion is dissipated in the wake, and the gain produced by the regeneration is equivalent to saving this other portion. /22

This assumes also that the pumping and expulsion system has an output equal to unity, which cannot occur in practice.

The minimal resistance could be calculated in the case of an ordinary output. In the case of a total or partial regeneration at a typical point, the resistance could also be easily calculated.

It is seen then that theoretically, if it is possible to reduce the friction by means of suction, the tangential forces themselves are not diminished. On the contrary, they are increased if the suction is performed at an intermediate point, since a layer of exhausted fluid with reduced speed is replaced by a layer of higher speed, thus corresponding to a greater local friction.

There is only one case in which one could hope to reduce the tangential forces themselves. This is the case in which the transition from the laminar area to the turbulent area is acted upon, by moving back the transition point. However, is suction capable of producing this event or does it produce the opposite result?

In the same spirit as the preceding considerations, Weske (in a study that appeared in 1939) performed research with the aim of diminishing the surface friction by streaming a fluid layer of reduced speed which has, among other effects, according to the author, that of delaying the appearance of turbulence. The advantage obtained would then be comparable to the loss of resistance appropriate to this process which, unlike the process studied above, corresponds to a diminution of surface friction but to an overall increase in resistance; and this is in spite of the energy that can be recovered in the streaming system and consequently, differences between the momentums suctioned and removed by this system.

b) <u>Case of Airfoils</u>

In the case of airfoils, what has been said about the tangential forces on a plate applies with certain modifications; if the suction takes place at a point where the pressure is less, for example, p_∞, the difference on the suction energy (assuming an output for the compressor), is more or less compensated by the kinetic energy of the suctioned fluid, which is greater and can be partially recovered in the streaming system. Certain differences also appear because of the fact that the slots cannot be made exactly tangential to the wall. The momentum equivalent to the suction thus has a component perpendicular to the wall; the upper surface is, however, compensated by the pressures on the edges of the slot at AM and DN (Figure 13), and by the well effect, which is translated by pressure differences on the sides AB and CD of the periphery of control and by the passage across /23
BC of a certain momentum. Relative indications can be found by calculating coefficients of lift and resistance, in the case of airfoils, with boundary layer control by means of suction, in the studies of Schrenk (20) and Bamber (24).

As far as the position of the slot in practice is concerned and the amount of fluid to suction in each particular case, it is seen that (bearing in mind what was said earlier for the case of the flat plate) there is interest in doing the following:

1. Setting the slot as near as possible to the trailing edge, i.e., just before the separation point corresponding to the evolution of the boundary layer by the boundary incidence that is intended to be reached.

2. Suctioning the amount of fluid strictly necessary so that the boundary layer, after the slot, does not separate before the trailing edge. If complete suction of the boundary layer does not produce this effect, it is necessary to provide a second slot. It follows that since the position of the slot is necessarily free, the best possible conditions are obtained when the amount of suctioned fluid varies with the region, i.e., with the incidence. In particular, at the values less than the boundary incidence, on this side of which no separation occurs, it is not necessary to apply suction.

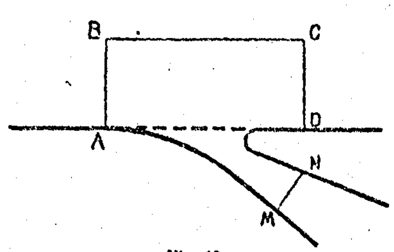


Fig. 13

c) Experiments of Schrenk and Bamber

Schrenk's experiments (22) involved a dense Karman-Trefftz profile, very different from the profiles used in practice. Since the suction compressors were located on the inside of the airfoil, practical considerations probably influenced that choice. Schrenk tested slots of different shapes and different lengths, placed in variable positions on the upper surface. The best results obtained are represented in infinite extension in Figure 14, which takes into account the power taken by the suction. The corresponding characteristics of the suction

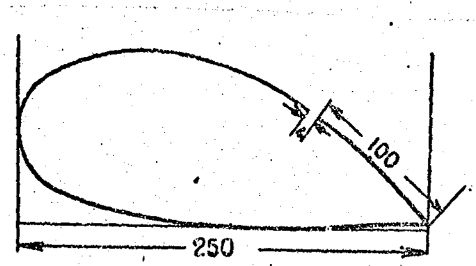
are given in the table accompanying this figure, in the form of /25
the coefficients c_q and c_p, correlated with the speed to infinity and to the projected surface of the wing. According to Schrenk, in this figure the envelope of all the curves obtained has been traced, taking into account, in certain cases, an extrapolation justified by the fact that the experimental conditions do not permit attainment of optimal suction in every case. From these curves it would be easy to deduce those in ordinary finite extension, with the implied resistance theoretically depending only on the lift and, consequently, the same with or without suction. This shows nicely how the theoretical lift is approached without being attained, up to values of c_z equal to 5.

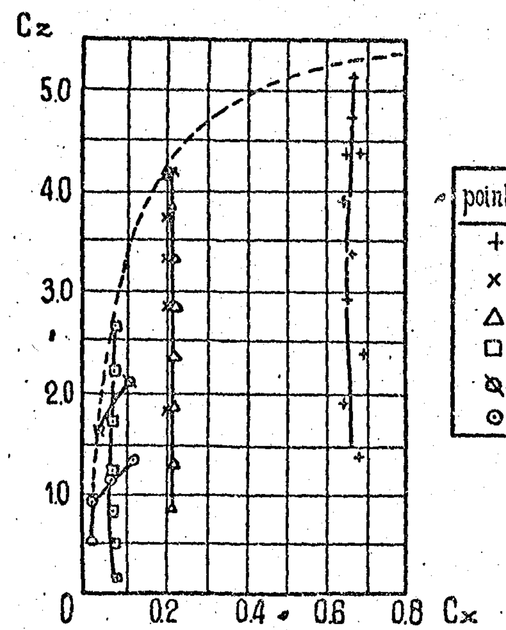
<u>Note</u>. - An important part of the trace of the dense profiles whose back ridge is angular is due to the fact that the pressure does not increase at that point up to the value of the total dynamic pressure, as the theory would predict. This effect is mainly due to the boundary layer, whose displacement thickness, by joining itself to the wall, comes to eliminate the rear angular point, on the wall and in the wake (Figure 16).

In eliminating the boundary layer by means of suction one should, from this act, regain a significant portion of the trace, by its incidence on the distribution of pressures. Experiments undertaken by Gerber (23) along these lines on two planes forming a re-entry angle effectively showed that the pressures could be increased in that region without it being possible, however, to attain the theoretical value.

Bamber's experiments were done on an N.A.C.A.M. 84 profile, with relative thickness less than that used by Schrenk, and indeed comparable to that of profiles used in practice.

The wing was tested between two circular plates, which corresponds





points	V m/sec	C_q	C_P
+	20	0.038	16.0
×	20	0.022	8.2
△	30	0.024	8.0
□	30	0.014	3.9
⊗	20	0.011	2 0
⊙	30	0.005	1 0

Figure 14

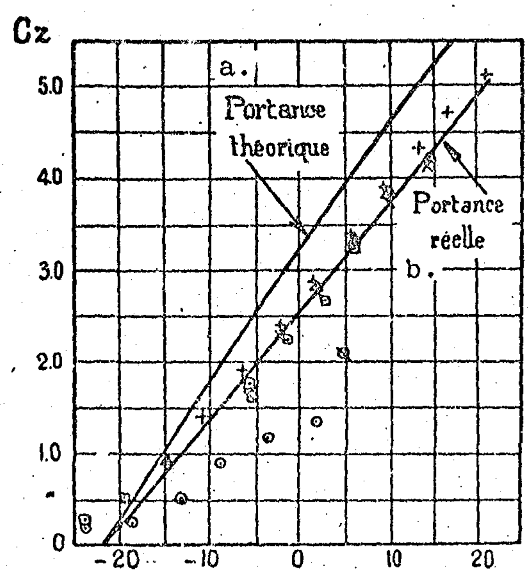


Figure 15. Result Taken to Infinite Extension

Key: a. Theoretical lift
b. Real lift

to a certain induced resistance, whereas Schrenk's were done between two parallel walls, with the resistance measured by probing the streaming.

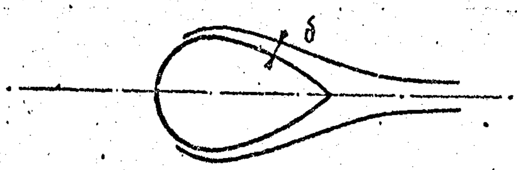


Figure 16

Bamber at the same time tested the suction and streaming systems. The slots used, however were the same in the two cases and were adjusted to the streaming; i.e., directed in the direction of the flow. This explains the results found by the author, which are noticeably more favorable for streaming than for suction.

The width of the slot used by Bamber was about 0.67% of the cord of the profile, whereas Schrenk found it advantageous to use a slot with a width of 3.8%. Bamber himself also recognized as probable that his results could have been improved by use of a wider slot.

Bamber's results are reported in Figure 17 and Figure 18, taken from the authors original report. In Figure 18, the lift coefficients are entered in order, as a function of the suctioned or streamed flows, and compared with the horizontal corresponding to the theoretical lift. It is seen that with suction, the theoretical lift can be exceeded. This fact can be explained by noting that in the case of suction, the speed on the back of the wing can never exceed the theoretical speed, since the streams replacing the exhausted boundary layer are taken within the sound fluid. By means of streaming, on the other hand, the energy of the replacement streams can be increased at will, and can produce an effect of ejection on the streams of the healthy flow, so that the circulation around the profile can be increased.

V. Application to Diffusers

The transformation of kinetic energy into pressure with the diffusers requires particular precautions which are not necessary for the reverse transformation and which are due to the thickening and to the danger of separation of the boundary layers. In the case of diffusers, the pressure gradient must not exceed certain limits, which imposes a certain length or a maximum angle on these parts. Despite these precautions and, in part because of the importance of the friction surfaces that result, their yield is only moderate and very much less than that of the parts that affect the reverse transformation. Whereas the latter have yields that are only a few percent less than unity, the yields of ordinary diffusers are only about 0.80 at maximum.

The problem of diffusers is thus at the same time a problem of yield and a problem of dimensioning. Boundary layer control by means of suction allows tolerance of more important pressure gradients and, consequently, attainment of far more rapid diffusions. The congestion of the equipment is reduced and it becomes possible in a given congestion, to obtain far more powerful diffusions. Naturally, as in the case of airfoils, in the evaluation of the output, it is necessary to take into account the power required for suction.

a) Diffuser Output

Various definitions can be conceived for the output of a diffuser. The problem can be that of maximum recovery, in the form of pressure of the kinetic energy of a given current. It is then logical to correlate the pressure increase obtained to the latter. The corresponding perfect diffuser thus would have an infinite terminal section.

An ordinary real diffuser then would only have an output less than unity, even with a perfect fluid, since the remaining kinetic energy would be counted as loss. Assuming the pressure and speed to be uniformly distributed in the intake and outlet sections, its maximum

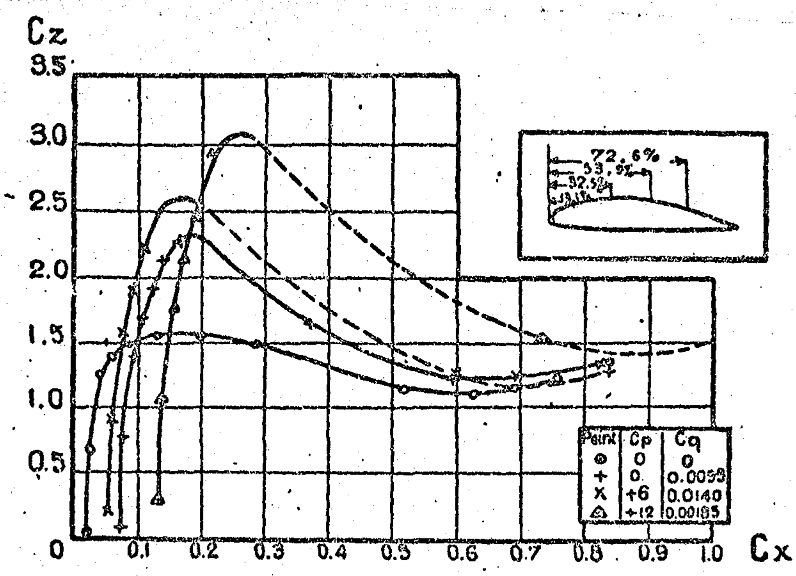


Figure 17

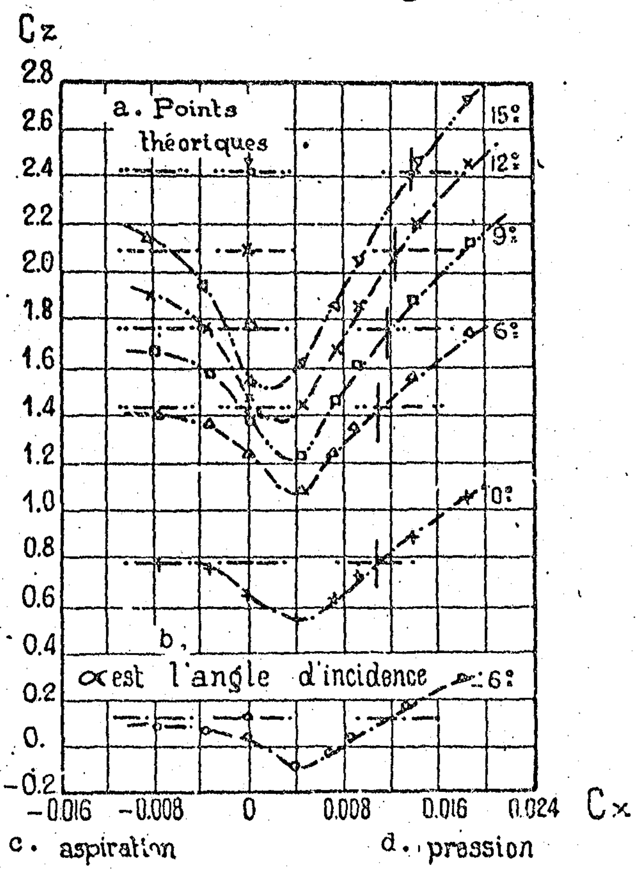


Figure 18

a. theoretical points
b. angle of incidence
c. suction
d. pressure

output would be:

$$\rho_{th} = 1 - \left(\frac{S_0}{S_1}\right)^2, \qquad (7)$$

with S_o and S_1 designating the intake and outlet sections.

Real diffusers corresponding to this problem in general open into an enclosure where the pressure is uniform (case of wind tunnels), so that their output can be determined by the measurement of that pressure alone, if the characteristics p_o and V_o at the entrance are assumed to be known. It is equal to:

$$\eta = \frac{P_1 - P_0}{\frac{\rho}{2} \cdot V_0^2}. \qquad (8)$$

This problem can also be slightly different and can correspond to the maximum recovery of a given kinetic energy for a fixed terminal section, corresponding, for example, to a pipe of arbitrary diameter. In this case, the remaining kinetic energy must not be counted as loss and the output of the perfect diffuser, having the desired terminal section, should be counted as equal to unity.

The output of a real diffuser can then be evaluated, according to the value of the energy losses which it causes, and the latter can be correlated either to the total kinetic energy in the intake section or to the portion of the latter which would be transformed into pressure in a perfect diffuser.

In the outlet section, the speeds are not homogeneous. Evaluation of the energy at this site should thus be done by a summation. Assuming the static pressure to be almost uniform, this is (Figure 19):

$$P_1 + \frac{1}{S_1 V_m} \int \frac{\rho}{2} V_1^3 \, ds_1,$$

with V_m designating the average speed in this section and ds_1, the element of air.

The output correlated to $\rho \frac{V_0^2}{2}$ then would be:

$$\eta = \frac{P_1 - P_0}{\rho \frac{V_0^2}{2}} + \frac{S_0^2}{S_1^2} \frac{1}{S_1} \int \left(\frac{V_1}{V_m}\right)^3 ds_1. \tag{9}$$

This expression, however, assumes that the kinetic energy of all the streams can be recovered. In the case of a flat plate with a current, the same conception would lead to the definition of a resistance coefficient by the value of the energy loss in the boundary layer and not by the total loss, including that which occurs in the wake. We can then, in a manner analogous to that allowing recovery of the value of the resistance coefficients, as they are customarily defined, assign to the diffuser the energy loss caused by the homogenization of the speeds. This last phenomenon, which is not produced within the diffuser itself but behind the outlet, is due to its defective functioning (Margoulis [25]). We have then:

$$\eta = \frac{P_1 - P_0}{\rho \frac{V_0^2}{2}} + \frac{S_0^2}{S_1^2}. \tag{10}$$

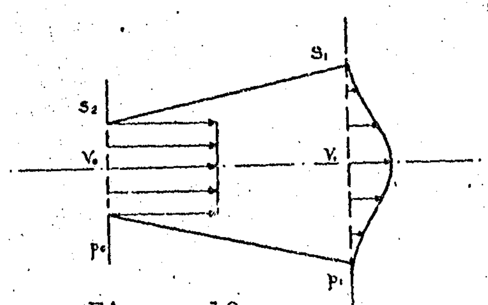


Figure 19

This expression itself can be discussed. If we admit, in effect, that the homogenization is produced in a pipe of constant diameter and that the friction on the walls of the latter is to be disregarded, as not being an integral part of the subject under investigation, the homogenization is not effected at a constant pressure. There is produced a slight pressure rise, due to the decrease of momentum that accompanies the regularization of the distribution of speeds and which is often confirmed experimentally.

If we admit that the homogenization is produced at a constant pressure, the momentum of the jet remains invariable and the speed, after regularization is the mean square speed, greater than the average speed. The pipe through which the stream would flow would /3
have a slightly decreasing diameter and it would be necessary, in the equation of the output, to introduce a slightly smaller section in place of S_1, which would be easy to calculate according to the distribution of speeds in the terminal section.

If the energy loss in the diffuser, increased by what is due to the homogenization of outgoing speeds, were correlated not to $\delta \frac{V_0^2}{2}$ but to the theoretical pressure increase in a perfect diffuser, i.e.,

$$\rho \frac{V_0^2}{2}\left[1-\left(\frac{S_0}{S_1}\right)^2\right]$$

the following expression for the output can easily be found:

$$\eta = \frac{P_1 - P_0}{\rho \frac{V_0^2}{2}\left[1-\left(\frac{S_0}{S_1}\right)^2\right]} \tag{11}$$

If boundary layer control by means of suction is performed, it is necessary to assume that the suctioned streams are returned to the fluid after the diffuser, with the same energy, i.e., at the same pressure and at the same average speed V_m. The energy thus expended should be added to the losses in the expression for the output. After this reversal, the section obviously increases and becomes the hypothetical section S'_1, equal to $\frac{S_1}{(1-\alpha)}$ if α is the proportion of the suctioned flow. The same formulas as for an ordinary diffuser can be applied by taking S'_1 instead of S_1 and, with the condition of adding to the losses the pumping power; this last amount is (with p' designating the pressure in the suction chamber - see Figure 20):

$$\alpha\left(p_1 + \rho \frac{V_m^2}{2} - p'\right),$$

so the output is finally

$$\eta = \frac{P_1 - P_0}{\rho \frac{V_0^2}{2}} + \left(\frac{S_0}{S_1}\right)^2 (1-\alpha)^3 - \alpha \frac{P_1 - P'}{\rho \frac{V_0^2}{2}}. \qquad (12)$$

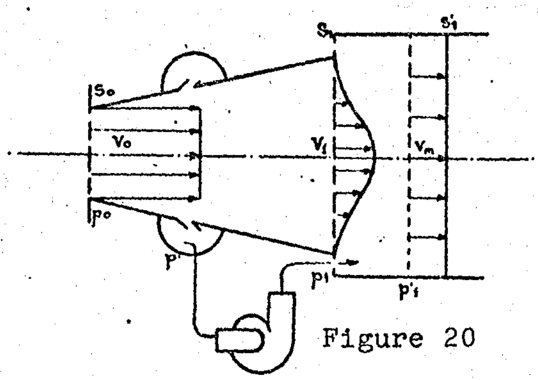


Figure 20

In his experiments, Ackeret [26] defines the output by correlating the pressure difference obtained $(p_1 - p_0)$ to the theoretical pressure increase, i.e.,

$$\rho \frac{V_0^2}{2}\left[1 - \left(\frac{S_0}{S_1}\right)^2\right].$$

increased by the energy expended by the suction, assuming the suctioned fluid to be brought to pressure p_1 without speed and taking into account an output of the pumping system equal to 0.75. With our notation, the expression he uses is as follows:

$$\eta = \frac{P_1 - P_0}{\rho \frac{V_0^2}{2}\left[1 - \left(\frac{S_0}{S_1}\right)^2\right] + \frac{\alpha}{0,75}(P_1 - P')}. \qquad (13)$$

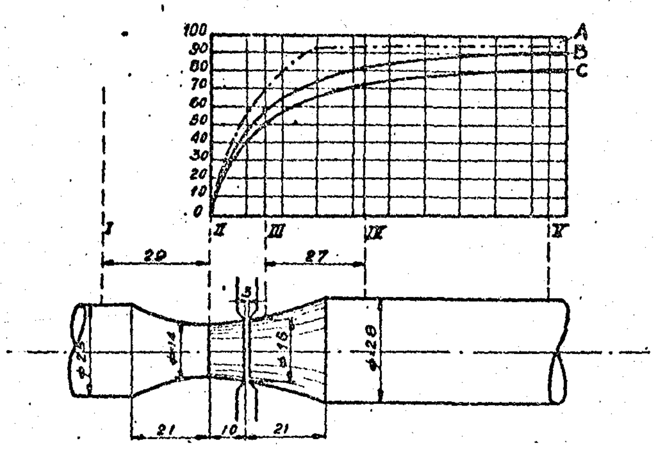


Figure 21

Margoulis [27] uses two different expressions, one of which corresponds to formula 12; with the assumption, however, that the suctioned fluid is recompressed to pressure p_1, but at null speed, which gives the following formula:

$$\eta = \frac{P_1 - P_0}{\rho \frac{V_0^2}{2}} + \left(\frac{S_c}{S_1}\right)^2 (1-\alpha)^2 - \frac{\alpha}{\eta_1} \frac{(P_1 - P'_1)}{\rho \frac{V_0^2}{2}}, \qquad (14)$$

with η as the output of the pumping system.

The other is analogous to formula 9, which in the case of suction can be written:

$$\eta = \frac{P_1 - P_0}{\rho \frac{V_0^2}{2}} + \frac{S_0^2}{S_1^2}(1-\alpha)^2 \frac{1}{S_1} \int \left(\frac{V_1}{V_m}\right)^3 ds - \frac{\eta_1}{\alpha} \frac{(P_1 - P'_1)}{\rho \frac{V_0^2}{2}}. \qquad (15)$$

c) Experiments of Ackeret and Margoulis

Ackeret's experiments [26] were performed with two diffusers with circular sections, having the same section ratio $\frac{S_1}{S_0} = 4$, and with lengths equal to 2.21 D_o and D_o respectively. Their profiles are given in Figures 21 and 22, taken from Ackeret's report. The angles at the apex (2θ) of the cones, having the same intake and output sections and the same length are 25^o4 and 53^o4 respectively. An annular vertical slot was installed at the distance equal to 1/3 of the diffuser's length, starting from the entrance section. The pressure in the suction chamber was constant and the variations in the suctioned flow were produced by a variation in the width of the slot.

The curves of the output as a function of α are represented in Figure 23 and are taken from an analysis of Ackeret's work, done by Pat. Paterson [28]. It is seen that an output greater than 0.8 was obtained in the two cases, with suctioned flow higher in the case of the diffuser with a larger angle, however. The ratio of the power expended for suction to the kinetic energy during the unit of time in the intake section of the diffuser $(\frac{W}{w})$, is shown as a function of α in Figure 23. The output of the suction apparatus is taken equal to 0.75.

The output represented in Figure 23 was calculated according to the values of the pressure discussed in Section IV, which is shown in Figures 21 and 22. According to the curve of static pressures, which was shown in the same Figures, a pressure increase is established in the pipe which follows the diffuser and probably corresponds, at least in part, to the phenomenon of homegenization of speeds which we noted above.

In Figures 21 and 22, the curve of theoretical pressures (calculated according to the value of the diffuser's cross sections) was also shown for comparison.

Margoulis' experiments were done on diffusers with rectangular

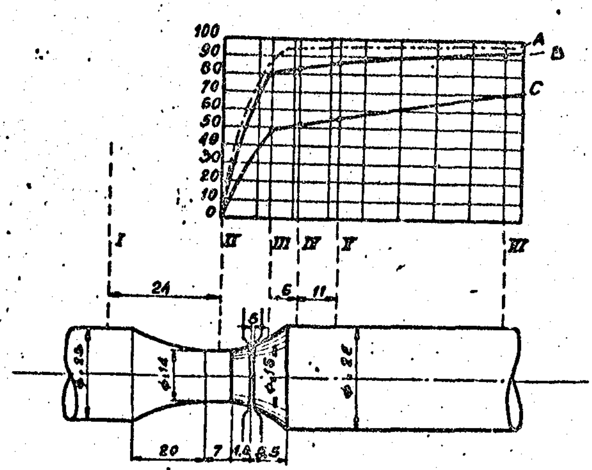


Fig. 22. A. Theoretical pressure; B. Real pressure with slot; C. Real pressure without slot.

sections consisting of two curved walls, placed between two parallel walls. The curved walls corres- /3
ponded to the same profile as Ackeret's long diffuser. The experiments were performed in open air on larger dimensions so that the Reynolds number of Margoulis' and Ackeret's experiments were about the same. The diffuser tested by Margoulis evidently corresponded to a section ratio only half that of Ackeret's and, therefore, to a smaller difference; and the equivalent cone, with the same length and the same intake and outlet sections, would have an angle of $5^{\circ}12'$ at the apex.

The 1.5 mm slots were placed in the sites indicated in Fig 24, with the position of the first one corresponding to the position of Ackeret's single slot. They all opened into the same chamber where suction was performed, so that the individual flows were not measured.

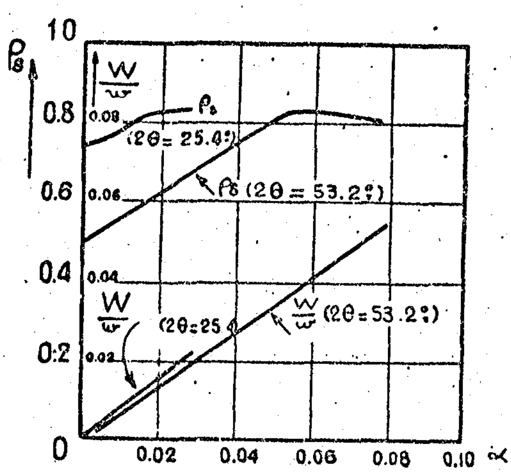


Figure 23

The best results were obtained when only the last two slots were open and an evaluation of the output, done by the author, resulted in a figure of about 0.93, whereas the output without any evacuation is about 0.8 (following formula 14).

The diffuser studied by Margoulis already corresponded to a good output, since it had a rather small difference, which is also indicated by the outlet probe taken without suction (Figure 24). According to this drawing, the separation that occurred still affected only a small part of the section. According to the same Figure, it is seen that suction brings about a good homogenization of the speeds.

VI. Conclusion

As early as 1904, Prandtl's first experiments showed that boundary layer control by means of suction was not a chimera and one might say that the experiments that took place later have amply confirmed the usefulness of the process.

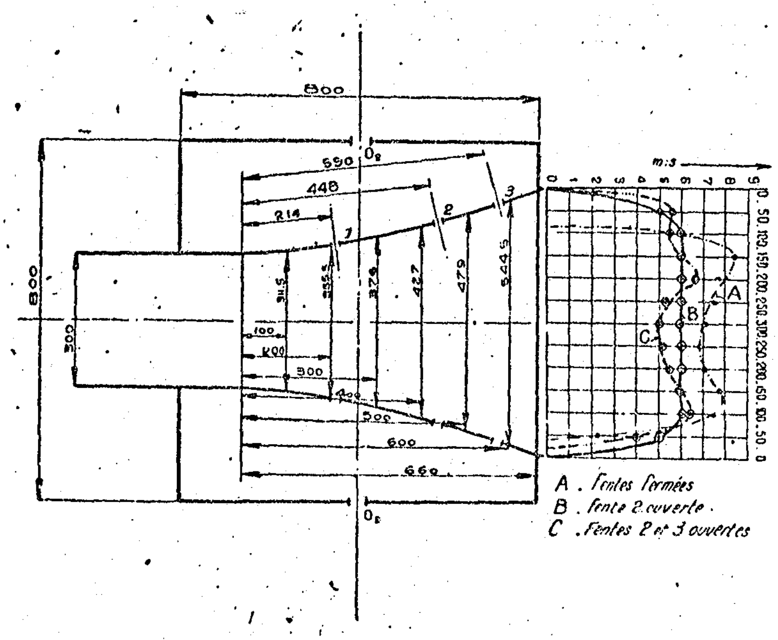


Fig. 24. Key: A. Closed slots; B. Slot 2 open;
C. Slots and 3 open

Its industrial applications, however, have not been as fully developed as might have been hoped. It may be that this is related to the complexity of the operation which requires a compression device.

As far as aviation is concerned, the great development in slotted airfoils (which do not present this inconvenience and which in practice allow substantial increases in lift), has certainly contributed to the hindrance of any development of airfoils with boundary layer control by means of suction. It is possible, however, that within this domain, their advantages will be more appreciated in the future, especially for machines with great speed and large operating range, which will require a rather large supplement to the lift upon take-off and landing, without harm to their normal aerodynamic qualities.

As far as diffusers are concerned, we shall cite a single industrial application of action upon the boundary layer, constituted in fact by streaming. It is the diffuser of the Moody hydraulic turbine. In this case it is evident - just as for airfoils and for the same reasons - that the economic benefit of the process cannot be fully justified in the case of large apparatuses. This is exactly the case of aerodynamic wind tunnels, which involve highly developed diffusers. The gain that could be obtained in the dimensioning must be able (as soon as large wind tunnels are involved) to compensate amply for the complication required by the suction equipment.

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